Int J Life Cycle Assess (2012) 17:1104–1115
DOI 10.1007/s11367-012-0424-9

PROMOTION OF YOUNG SCIENTISTS IN LCA

Life cycle assessment of the supply and use of bioenergy: impact of regional factors on biogas production

Daniela Dressler · Achim Loewen · Michael Nelles

Received: 17 March 2011 / Accepted: 29 March 2012 / Published online: 20 April 2012

Abstract
Purpose This article evaluates the parameters that influence the results of a life cycle assessment (LCA) of biogas production from maize and the conversion of biogas into electricity. The environmental impacts of biogas vary according to regional farming procedures and, therefore, the soil, climate conditions, crop yield, and cultivation management. This study focuses on these regional parameters and the existing infrastructure, including the number of installed biogas plants and their share of used heat.
Materials and methods To assess the regional impact, the LCAs of maize cultivation, on the one hand, and the production and use of biogas, on the other, were performed for three different areas. These areas were the administrative districts of Celle, Hildesheim, and Goettingen; all located in the south of Lower Saxony, Germany. The areas differed in geographic location conditions, crop yield, and the number of installed biogas plants. The necessary data for modeling the cultivation of maize were derived from the specific regional and local parameters of each area. The most important parameters were the soil characteristics and the climate conditions for cultivating maize. The share of used heat from combined heat and power unit (CHP) was another relevant factor for biogas production and use.
Results Our results demonstrate significant differences among the investigated areas. The smallest environmental impact of all the considered categories occurs in Goettingen and the largest in Celle. The net greenhouse gas emissions vary from 0.179 kg CO_2 eq./kWh$_{el}$ in Celle to 0.058 kg CO_2 eq./kWh$_{el}$ in Goettingen. This result is due to the maize cultivation system and the different credits for using heat from the CHP. Variances in energy crop cultivation result from different nitrogen and irrigation demands. In addition, despite higher applications of nitrogen fertilizer and irrigation, the maize yield is lower in Celle. The impact category of total fossil energy shows similar results to that of the greenhouse gas (GHG) emissions. The results range from −0.274 to 0.175 kWh/kWh$_{el}$. The results of acidification and eutrophication vary from 1.62 in Goettingen to 1.94 g SO_2 eq./kWh$_{el}$ in Celle and respectively 0.330 to 0.397 g PO_4^{3-} eq./kWh$_{el}$. These differences are primarily caused by maize cultivation, especially irrigation.
Conclusions and perspectives Cultivating maize and using waste heat from the CHP were identified as the most influential parameters for the GHG emissions and total fossil energy demand. Regarding acidification and eutrophication, the most relevant factors are the application of digester output and the emissions from the CHP. Our results show the need to consider regional parameters in the LCA of bioenergies, particularly biogas production and use, especially if the LCA studies are used for generalized evaluations such as statements on the climate protection potential of biogas.

Keywords Bioenergy · Biogas plant · Cultivation concept · Energy crops · LCA · Regional parameters

1 Introduction

The importance of the production and use of biomass to generate power, heat, and fuels is increasing on a global scale. International and national policies, such as the European Biomass Action Plan, support the expansion of bioenergy because bioenergies are considered to be climate friendly compared to

D. Dressler (✉) · A. Loewen
Faculty of Resource Management, University of Applied Sciences and Arts, Hildesheim/Holzminden/Goettingen,
Büsgenweg 1a,
37077 Goettingen, Germany
e-mail: dressler@hawk-hhg.de

M. Nelles
Faculty of Agricultural and Environmental Sciences,
University of Rostock,
Justus-von-Liebig-Weg 6,
18059 Rostock, Germany

their fossil alternatives. In addition, bioenergies supposedly reduce the high dependency on imports of fossil fuels of many European Union countries (Commission of the European Communities 2005). However, the production and use of bioenergies are connected to the release of greenhouse gases and other environmental impacts, such as acidification and eutrophication. Therefore, the environmental and climate benefits of bioenergies must be verified according to life cycle assessment (LCA) methods (ISO 14040 2006; ISO 14044 2006).

Since the beginning of the 1990s, several studies have analyzed the environmental performance of different bioenergies compared to fossil fuels. For instance, relevant studies have evaluated biogas production and the conversion of biogas into electricity (Wuppertal Institute 2005; Hartmann 2006; Bachmaier and Gronauer 2008; IFEU 2008a; Juri et al. 2009). These studies have shown a wide range of results. The greenhouse gas (GHG) emissions of electricity generation from biogas vary from −0.143 to 0.160 kg CO_2 eq./kWh_{el} (Bachmaier and Gronauer 2008).

This range derives from different parameters. The ISO 14040/44 framework standardizes the method; yet, it offers several options for performing LCAs. One option is to consider different allocation processes regarding by-products. Recently, this process has been intensely discussed, especially for bioenergy; for instance, the studies of Luo et al. (2009) and Majer and Schröder (2009) demonstrated a wide range of GHG emissions. Therefore, the allocation of by-products was clearly defined within a sustainable directive for bioenergies for the first time. The allocation processes of by-products had to be based on their calorific value (Majer and Schröder 2009).

In addition to the allocation processes, regional parameters and local factors might influence the results of bioenergy LCAs. For example, Kim and Dale (2009) showed regional variations in GHG emissions from corn-based ethanol and soybean oil production in 40 different counties in USA. The investigations were based on the evaluations of survey results. Cultivating energy crops with the resulting nitrous oxide emissions from the soil and N fertilizers are identified as the highest GHG emission sources, with a share of 13–57 % of all GHG emissions (Kim and Dale 2009).

Our investigation is not based on survey results but on regional parameters, such as soil and climate, and on existing infrastructure, including the number of installed biogas plants. The main goal of this paper was to identify and discuss the influences of regional parameters and local factors on the results of LCAs of biogas production from maize and the use of biogas for power generation.

2 Materials and methods

This study follows the ISO 14040/44 2006 standards for generating LCAs. Furthermore, the study was based on data collected in the joint research project "Regional management of climate impacts in the metropolitan region of Hannover-Braunschweig-Goettingen (KFM)," which was funded by the German Federal Ministry of Education and Research.

2.1 Investigated crops and bioenergy process

The influences of regional parameters and local factors on the results of LCAs were identified and discussed based on the example of cultivation silage maize for biogas production and the use of biogas for power generation. This section describes the reasons for choosing maize as an investigated energy crop and biogas as a bioenergy process. Maize is an important energy crop on a global scale. However, in the cultivation and energetic use of maize, grain maize must be distinguished from silage maize. In silage maize, the whole plant is harvested and used, while in grain maize, only the corncob is used. Grain maize is used in the food sector or for the production of bioethanol, but the cultivation of grain maize is less widespread in Europe, particularly in Germany, than in the USA, China, Brazil, or Mexico (FAO 2009). In Europe, silage maize is mainly cultivated and used as animal feed, but silage maize is also used for biogas production, especially in Germany. In 2010, Germany produced more than 75 million tons of silage maize, with a cultivated area of 1.85 million ha, which represented 30 % of the total cultivation area of silage maize in the EU 27 (DMK 2011). Furthermore, more than one third of the produced silage maize was used for biogas production in Germany. Silage maize for biogas production is therefore the most important energy crop in Germany after rapeseed for rapeseed oil and biodiesel production. Rapeseed was cultivated in an area of approximately 900,000 ha in 2007 (FNR 2011).

Regarding renewable energy production in Germany, biogas production and use had a share of 13 % of the overall renewable electricity and a share of 6.6 % of the overall renewable heat in 2010. Biofuels from biogas are negligible. Rapeseed oil and biodiesel represent only a minor contribution (13 %) to the production of renewable electricity and heat. Therefore, the production of biogas from silage maize is an essential source of renewable energy in Germany. Moreover, silage maize (hereafter called maize) is the most important energy crop because it constitutes 80 % of the substrates for biogas production in Germany (IFEU 2008b).

2.2 Investigated regions

The chosen research areas are the administrative districts of Celle, Hildesheim, and Goettingen; all located in the metropolitan region in the south of Lower Saxony, Germany. The regions differed in geographic location, soil conditions, crop yield, and the number of installed biogas plants. The soil in

Hildesheim and Goettingen is primarily composed of clay and silt. In Hildesheim, the soil has high fertility and natural yield factors, which result in an average soil quality of 63 out of 100 possible points (German scale of soil quality). In Goettingen, an average soil quality of 50 represents a median natural yield factor caused by the higher altitudes in the southwest of Lower Saxony. The district of Celle has primarily sandy soils and, therefore, a low natural yield factor with an average soil quality of 30 (LBEG 2010). These yield levels influence the types of cultivated crops. While cash crops such as winter wheat and winter barley, with high requirements of soil and water supply (Lewandowski and Böhmel 2009), were the dominating cultures with a share of 50 % in Göttingen and Hildesheim, these crops did not play an important role in Celle, a district with low natural yield factors (LSKN 2007).

The number of installed biogas plants and the land that is used for cultivating maize were not related to the high yield levels. With a share of 13 %, maize cultivation is an important sector of the agricultural land use in the district of Celle but has less importance in Goettingen and Hildesheim, where its shares are 2–5 % (LSKN 2007).

The extension of maize cultivation is due to Germany's renewable energy legislation (EEG 2009), which supports the production of electricity from biogas. Even on dry and poor soils, such as those found in the district of Celle, the cultivation of maize is economically feasible. Thus, Celle has 35 installed biogas plants, whereas Hildesheim and Goettingen have only 14 and 9, respectively. These biogas plants were mainly built in rural areas with a low heat demand, which led to an average use of the produced heat of only 30 % in Celle. In Goettingen and Hildesheim, the share of heat used was higher and reached approximately 60 % in the district of Goettingen. These parameters were important for determining the life cycle inventory data, which were dependent on different regional and local conditions within the three investigated areas (Table 1).

2.3 Goal and scope

The goal of this study was to assess the impact of regional factors on the results of the LCAs of maize cultivation as well as on the production and use of biogas. Therefore, three LCAs were generated for the different areas of the KFM project (see Section 2.2.) considering their regional and local conditions.

2.4 System boundaries

The system boundaries of the three LCAs for Hildesheim, Celle, and Goettingen were cradle to grave. Thus, the burden of all input processes of the whole life cycle from raw material acquisition or the generation from natural resources was included. These inputs included maize cultivation, maize transportation to biogas plants, production and use of biogas, and recycling of digester output as fertilizer. The production of farm equipment (e.g., tractors), biogas plants, and infrastructure (e.g., roads, trucks) were not included in the system boundaries. However, the life cycle assessment of industrial-scale biogas plants by Hartmann (2006) showed only a small contribution of approximately 4 % to the total impact. The life cycle inventory was based on the 2007–2010 period.

2.5 Functional unit

This study focused on two different aspects of the regional impact on the LCA results: agricultural processes (maize production) and bioenergy production (electricity produced from biogas). For these reasons, the LCA results were based on two different functional units. One functional unit was defined as 1 kg fresh matter of maize. The other functional unit was defined as 1 kWh of electricity produced in a combined heat and power generation plant (CHP) using biogas.

2.6 Sources of inventory data and software

The necessary data for modeling the cultivation of energy crops such as maize depended on specific regional parameters and local factors. The most important parameters were the soil and climate conditions. As a result, different fuel consumption levels for fieldwork (KTBL 2006), regional differences in irrigation demand (Fricke and Riedel 2010), and varying maize yields could be derived (LSKN 2007).

The fuel consumption for cultivation based on the database of the Association for Technology and Structures in Agriculture (KTBL 2006) depended on district-level soil conditions. Therefore, Celle was defined as a district with light soil conditions, Göttingen as a district with middle soil conditions, and Hildesheim as a district with heavy soil conditions. The irrigation demand for maize cultivation in the district of Celle was obtained from field trials performed by the Chamber of Agriculture of Lower Saxony. District-level maize yield data were available at the Centre for Statistics and Communications Technology of Lower Saxony (LSKN 2007). The amount of fertilizers to be applied was calculated based on the crop-specific guiding values of the Chamber of Agriculture of Lower Saxony. For maize, this guiding value was as high as 180 kg N fertilizer/ha (LWK 2009). The district-level demand for nitrogen was determined by the N_{min} method, with specific N_{min} values for each region. Consequently, the N reference value of maize was as high as 180 kg N/ha minus the specific N_{min}-value (LWK 2010a, 2010b). Based on these nitrogen demands and the Intergovernmental Panel on Climate Change (IPCC) method (2006), nitrous oxide emissions were calculated in the following manner: direct emissions with 1 %/kg N applied and indirect emissions with 0.37 %/kg N applied

Table 1 Soil quality, agriculture area and installed biogas plants including the share of used heat within the areas of Celle, Hildesheim, and Göttingen

Investigated area	Soil quality[a]	Agriculture area[b] (ha)	Cultivating maize[b] (ha)	Installed biogas plants[c]	Share of used heat[c] (%)
Celle	30	49,432	8,608	35	30
Hildesheim	63	64,559	3,301	14	40
Göttingen	50	40,171	1,672	9	60

[a] LBEG 2010

[b] LSKN 2007

[c] KFM-project

(as ammonia loss and leaching). In addition to ammonia emissions, methane emissions and nitrogen-related emissions caused by losses from applying digester output and leaching were calculated based on field trials performed by Hartmann (2006). These field trials referred to a soil that was mainly composed of clay and silt, such as the soil in the districts of Hildesheim and Goettingen. All data necessary for modeling the maize cultivation for each district, including the specific yield, are summarized in Table 2.

The assumptions for calculating the production and use of biogas in a combined heat and power plant were the same for each district, with the exception of the share of used heat. These values were calculated according to the differences shown in Section 2.4 and Table 1. Likewise, Table 3 summarizes all of the data necessary for modeling the production and use of biogas for each district.

Maize transportation from the field to the biogas plants was taken into account as 20 km on average for each district following the economic value. This distance might need to be checked in further studies concerning its regional aspect. In districts with a higher number of installed biogas plants, such as the Celle district, it might be possible to achieve longer transport distances than those in the Göttingen or Hildesheim regions because of competition. The storage and silage of maize were calculated with a loss of 12 % of weight according to KTBL (2006). Maize properties for biogas production based on KTBL (2009) were defined as 33 % dry matter, 95 % organic matter, 650 l_N/kg organic matter biogas yield, and 52 % methane content. The energy efforts (electricity and process heat) of biogas production were assumed according to the surveys of the KFM project. An energy crop biogas plant requires 256 kWh process heat per m_N^3 of produced biogas and, on average, 7 % of the produced electricity.

Approximately 1 % of methane was released as diffuse emissions from the fermenters during the fermentation process. This value is based on an estimation of IFEU (2008a) and is currently reviewed in a study by Liebetrau et al. (2011). Within the study at hand, there are no regional data on the storage of digester output, and as a result, the storage of digester output was assumed to be gas-tight. This assumption was based on the guidelines of the EEG (2009) (German Renewable Energy Sources Act): all new biogas plants need covered storages for digester output. In the case of older biogas plants (put into operation between 2004 and 2009), covered storage is not obligatory, and the release of methane emissions would be much higher (IFEU 2008a; Liebetrau et al. 2011). This fact will be investigated according to the regional differences in further studies.

Table 2 Yield, agronomic inputs (fertilizers, herbicides, irrigation, and fuel consumption) and direct and indirect nitrous oxide emissions from soil in maize cultivation

Parameter	Unit	Hildesheim	Göttingen	Celle	Reference
Yield	dt/ha FM	468.8	437.5	398.1	LSKN 2007, KFM project
Digester output	m^3/ha FM	20	20	20	
Nitrogen fertilizer	kg N/ha	83	68	77	LWK 2010a, 2010b
Phosphorus (P_2O_5) fertilizer	kg P_2O_5/ha	55	51	51	LWK 2010c
Potassium (K_2O) fertilizer	kg K_2O/ha	82	73	73	LWK 2010c
Magnesium (MgO) fertilizer	kg MgO/ha	32	32	32	LWK 2010c
Herbicides	kg/ha	1.5	1.5	1.5	TLL 2007
Fuel	l/ha	82.9	69.9	66.4	KTBL 2006
Irrigation	mm/m^2	–	–	610	KFM project
Direct nitrous oxide emissions	%/kg N	1	1	1	IPCC 2006
Indirect nitrous oxide emissions	%/kg N	0.37	0.37	0.37	IPCC 2006

Table 3 Transport distance, fermentation values (maize properties, biogas yield, methane content, methane losses, heat, and power requirement) and characteristics of CHP (electrical power, electrical efficiency, thermal efficiency, and methane losses)

Parameter	Unit	Hildesheim	Göttingen	Celle	Reference
Transport distance	km	20	20	20	
Transport and silage losses	% by weight	12	12	12	KTBL 2006
Maize properties					
Dry matter	%/kg fresh matter	33	33	33	KTBL 2009
Organic matter	%/kg dry matter	96	96	96	KTBL 2009
Biogas yield	l_N/kg organic matter	650	650	650	KTBL 2009
Methane content	%/m_N^3 biogas	52	52	52	KTBL 2009
Methane losses from fermenter	%/m_N^3 methane	1	1	1	IFEU 2008a
Power requirement	%/kWh generated power	7	7	7	KFM project
Heat requirement	kWh/m_N^3 biogas	0.256	0.256	0.256	KFM project
Characteristics of CHP					
Electrical power	kWh	255	255	255	KFM project
Electrical efficiency	%	40	40	40	ASUE 2011
Thermal efficiency	%	48	48	48	ASUE 2011
Methane losses CHP	%/m_N^3 methane	0.5	0.5	0.5	IFEU 2008a

Biogas was used in two CHP gas engines to produce electricity and heat. Each CHP unit had an installed capacity of 255 kW, an electrical efficiency of approximately 40 %, and a thermal efficiency of approximately 48 %. In this context, the methane loss from the CHP was calculated as 0.5 % during combustion (IFEU 2008a). However, flue gas was treated in an oxidizing catalytic converter, which reduced the absolute NMVOC emissions by 70 %, CO emissions by 75 %, and methane emissions by 50 % (GEMIS 2010).

Further data needed for the life cycle inventory, especially for upstream processes such as power generation, were obtained from the databases of the ecobalancing software GaBi (PE International 2010) and GEMIS (GEMIS 2010). The modeling and calculation of the LCAs were also performed using the ecobalancing software GaBi 4.4.

2.7 Allocation processes

By-products were considered for the expansion of the system boundaries and credits for substitute processes. The system expansion was used to describe the environmental benefit of using biogas sludge as a by-product of the biogas process and the heat from the CHP unit. Therefore, the environmental burden associated with the production of the same quantity of mineral fertilizer (NPK), which could be substituted by digester output, was subtracted from the total burden of the whole biogas life cycle. However, emissions from the utilization of digester output had to be considered. The quantity of mineral fertilizers substituted was defined considering the amount of digester output and its nutrient content. The amount of digester output results from fresh matter input and its degradation rate. For silage maize, the degradation rate is 24 % of fresh matter. The nutrient contents were determined within the KFM project and are listed in Table 4.

Heat, as a by-product of the CHP unit, was considered in the same way; the environmental impact of generating heat from oil and natural gas were credited to the system. The credit for heat was calculated based on the surplus heat and the share of used heat. The shares of used heat were assessed within the KFM project and ranged from 30 to 60 % as annual averages. The value of 60 % for the district of Goettingen is an especially high annual average and is not usual. However, in Goettingen, most of the biogas plants are either a part of a bioenergy village with almost 50–60 % heat use as the annual average or used for production of thermal process energy with almost 100 % heat use as the annual average. The significance of the assessed shares of heat use is discussed in Section 4.

The reference processes used for heat and fertilizer credits, including all necessary parameters, are shown in Table 4. A sensitivity analysis of this allocation procedure was included for the CHP units as a comparison of allocation based on exergy.

2.8 Life cycle impact assessment

Experts and politicians attribute the reduction of greenhouse gas emissions and saving of fossil energy demand as important criteria in the context of the assessment of biogas. Nutrient discharges and acidification are also important environmental effects of biogas production, especially the application of biogas sludge. This study focused on these important impact categories: global warming potential (GWP), acidification potential, eutrophication potential, and total fossil energy demand. Other impact categories, such as ozone depletion or toxicity,

Table 4 Reference processes for allocation (credit for digester output and credit for heat use from CHP)

Reference process	Parameter	Unit	Quantity	Reference
Credit for digester output (dig.-out)				
	Degradation rate of maize	m^3 dig.-out/kg maize	0.76	KTBL 2009
Calcium ammonium nitrate (CAN) (27 %N)	N content	kg N/m^3 dig.-out	5.2	KFM project and KTBL 2009
Triple superphosphate (TSP) (45 % P_2O_5)	P content	kg P_2O_5/m^3 dig.-out	2.2	KFM project and KTBL 2009
Potassium chloride (KCl) (60 % K_2O)	K content	kg K_2O/m^3 dig.-out	6.1	KFM project and KTBL 2009
Magnesium sulfate (16 % MgO)	Mg content	kg MgO/m^3 dig.-out	0.4	KFM project and KTBL 2009
Credit for heat use				
	Heat output	kWh_{th}/kWh_{el}	1,2	
	Surplus heat	kWh_{th}/kWh_{el}	1,08	
	Share of used heat	% of surplus heat	See Table 1	KFM project
German technology mix for production of thermal energy from natural gas	Share of gas-fired heating	%/% share of used heat	40	Assumption within the KFM project
German technology mix for production of thermal energy from fuel oil	Share of oil-fired heating	%/% share of used heat	60	Assumption within the KFM project

have not been taken into account in this study. The climate change was calculated for a 100-year time frame based on GHG emissions indicated as CO_2 equivalents (eq.) and defined by the IPCC (2007). Acidification and eutrophication by gaseous emissions are measured in SO_2 eq. and PO_4^{3-} eq., respectively. These factors were calculated based on the characterization factors of the Institute of Environmental Science of Leiden University (CML; Guinée et al. 2002). The total fossil energy demand was calculated by multiplying the total amount of each fossil fuel needed with its calorific value (primary energy content) plus the total nuclear energy demand of nuclear power generation (VDI 4600 1997). Therefore, in this study, all results of the total fossil energy demand include the nuclear energy demand, as well, to simplify matters.

3 Results

3.1 Impact assessment of energy maize cultivation

The results from the impact assessment for cultivating maize are summarized in Table 5 and demonstrate a range in the results among the investigated areas. The greatest environmental impact of all the considered categories occurs in Celle.

Table 5 Results from the impact assessment of cultivating maize (greenhouse gas emissions, total fossil energy demand, acidification, and eutrophication)

	Total	Nitrous oxide emissions	Fertilizers and pesticides	Applying digester output	Irrigation	Fieldwork
Greenhouse gas emissions [kg CO_2 eq. t^{-1}]						
Göttingen RD	45.4	25.0	15.1	0.5	0	4.8
Celle RD	57.7	28.9	18.2	0.5	5.1	5.0
Hildesheim RD	47.9	25.5	16.6	0.5	0	5.3
Total fossil energy demand [kWh t^{-1}]						
Göttingen RD	67.3	0	48.7	0	0	18.6
Celle RD	95.8	0	56.8	0	19.6	19.4
Hildesheim RD	72.0	0	51.4	0	0	20.6
Acidification [g SO_2 eq. t^{-1}]						
Göttingen RD	268.8	0	29.0	202	0	37.8
Celle RD	370.3	0	33.9	222	73.7	40.7
Hildesheim RD	258.8	0	30.9	188	0	39.9
Eutrophication [g PO_4^{3-} eq. t^{-1}]						
Göttingen RD	77.4	23.4	9.8	37.5	0	6.7
Celle RD	101	27.1	12.1	41.2	13.4	7.2
Hildesheim RD	76.9	23.8	11.1	35.0	0	7.0

The GHG emissions associated with cultivating maize range from 45.4 to 57.7 kg CO_2 eq./t of fresh maize. Direct and indirect nitrous emissions from the soil, with 50 to 56 % of the total GHG emissions, represent the most significant source for each district. The lowest levels of GHG emissions occur in the district of Goettingen because of this region's lower demand for fertilizers, pesticides, and fuel for fieldwork. In the district of Celle, the cultivation of maize produces the highest GHG emissions. The reasons for these higher emissions are a lower yield of maize, higher demand of fertilizers in conjunction with higher nitrous emissions from the soil, and required irrigation. The GHG emissions from irrigation in Celle reached 5 kg CO_2 eq./t of fresh maize (9 % of the total GHG emissions). Thus, irrigation in Celle results in as many emissions as the whole fieldwork of each district.

The total fossil energy demand associated with maize production is 63.7 to 95.8 kWh/t of fresh maize. Similar to the results for the GHG emissions, the irrigation demand in the district of Celle and the higher fertilizer efforts during the cultivation of maize cause the observed regional variations. Between 59 and 72 % of the total fossil energy demand is caused by the supply of fertilizers and pesticides. Fieldwork requires a total fossil energy demand between 20 and 28 % in addition to the fossil energy demand for irrigation in the district of Celle (21 %).

The acidification associated with the cultivation of maize ranges from 258.8 to 370.3 g SO_2 eq./t of fresh maize (see Table 5). The ammonia emissions resulting from the application of digester output are the primary acidification source, followed by nitrogen dioxide emissions from fuel combustion for the irrigation system (only in the district of Celle) and fieldwork. The regional differences in acidification are mostly caused by nitrogen oxide emissions from fuel combustion irrigation systems, followed by different nitrogen demands and, consequently, a different application level of digester output.

The emissions from the eutrophication impact category range from 76.9 to 101 g PO_4^{3-} eq./t of fresh maize. These values are primarily caused by ammonia–nitrogen emissions from applying digester output, followed by nitrous oxide emissions from the soil. The regional variation in eutrophication is caused by the same effects as those of acidification.

3.2 Impact assessment of the production and use of biogas

The results of the impact assessment of the production and use of biogas are shown in Figs. 1, 2, 3, and 4. These results demonstrate similar findings as those of the impact assessment of the cultivation of maize, i.e., differences among the investigated areas in all assessed impact categories. The smallest environmental impacts of the evaluated criteria occur in Goettingen, and the greatest impacts occur in Celle.

The GHG gross emissions within the GWP impact category range from 0.248 (Goettingen) to 0.281 kg CO_2 eq./kWh_{el} (Celle). This pattern is due exclusively to maize cultivation because the inventory assumes as a common basis of the same technical process and efficiency factors for producing biogas from maize and converting it into electricity. The variances in energy crop cultivation and their impact on the LCA are discussed in Section 3.1. The largest GHG emissions sources in all three areas derive from maize cultivation (48–54 %). More than 18 % of the GHG gross emissions are caused by the energy demand (heat and power) for biogas plant operations, followed by methane losses during the biogas process (16 to 18 %). Therefore, methane losses of 1 % represent an important contribution to the GHG balance. The GHG emission credits for using heat from CHP and credits for using digester outputs as fertilizer are shown in the negative side of the *x*-axis in Fig. 1. The credits for heat use range from 0.102 to 0.190 kg CO_2 eq./kWh_{el}. This difference is caused by a higher share of used heat in Goettingen. Therefore, the net GHG emissions vary from 0.179 in Celle to 0.058 kg CO_2 eq./kWh_{el} in Goettingen (see Fig. 1). The GHG emissions in Hildesheim are similar to those of Goettingen, but they are still higher due to the lower heat use rates than in Goettingen.

The results of the impact category of total fossil energy demand are shown in Fig. 2 and are similar to the results of the GHG emissions. Net results vary from −0.274 to 0.175 kWh/kWh_{el}. Similar to the GHG emission results, the cultivation of maize and especially the lower credit for using heat from CHP in Celle cause regional variations. Regarding the gross results, the fossil energy demand ranges from 0.468 to 0.543 kWh/kWh_{el}. This outcome demonstrates the high impact of heat recovery, which can even lead to negative net values, as in Göttingen. Therefore, the impact of credits for heat use is considered separately in the sensitivity analysis.

The acidification and eutrophication findings, shown in Figs. 3 and 4, are different from the results of the GHG emissions and the accumulated fossil energy demand. The credits for using the exhaust heat from CHP are considerably smaller and have a significantly lower impact on the net results.

The acidification net emissions vary from 1.62 in Goettingen to 1.94 g SO_2 eq./kWh_{el} in Celle. These differences are primarily caused by maize cultivation and especially by irrigation. However, the emissions from applying the digester output account for the largest share, followed by the NO_x emissions from the combustion of biogas in the CHP (more than 30 % of the gross emissions) in each district. The emissions of the eutrophication impact category range from 0.330 to 0.397 g PO_4^{3-} eq./kWh_{el} and are caused by the same effects of the emissions relevant to acidification.

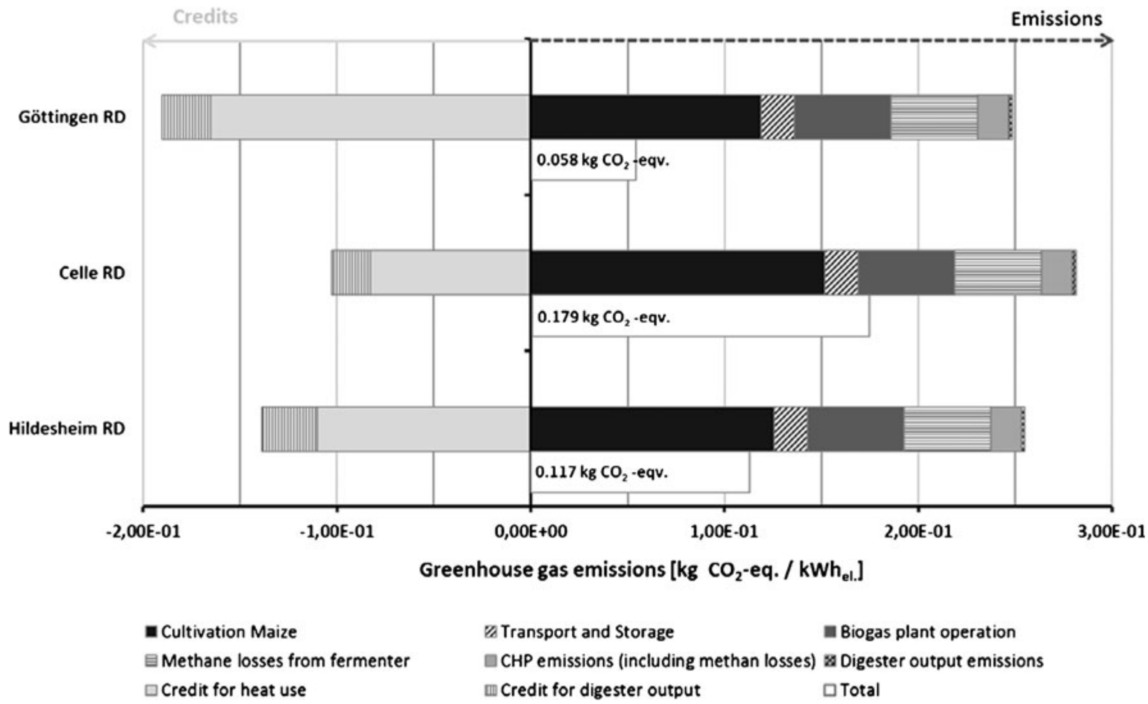

Fig. 1 GHG emissions of power generation from biogas in Göttingen, Celle, and Hildesheim [*left side* GHG credits, *right side* GHG emissions, and *lower bar* total result]

3.3 Sensitivity analysis

The credits for heat use have an important impact on the GHG emissions and the total fossil energy demand impact categories. Therefore, these credits constitute relevant factors for regional variations in the LCA results. The sensitivity analysis verifies if this important contribution depends on the system expansion, which was used as an allocation procedure.

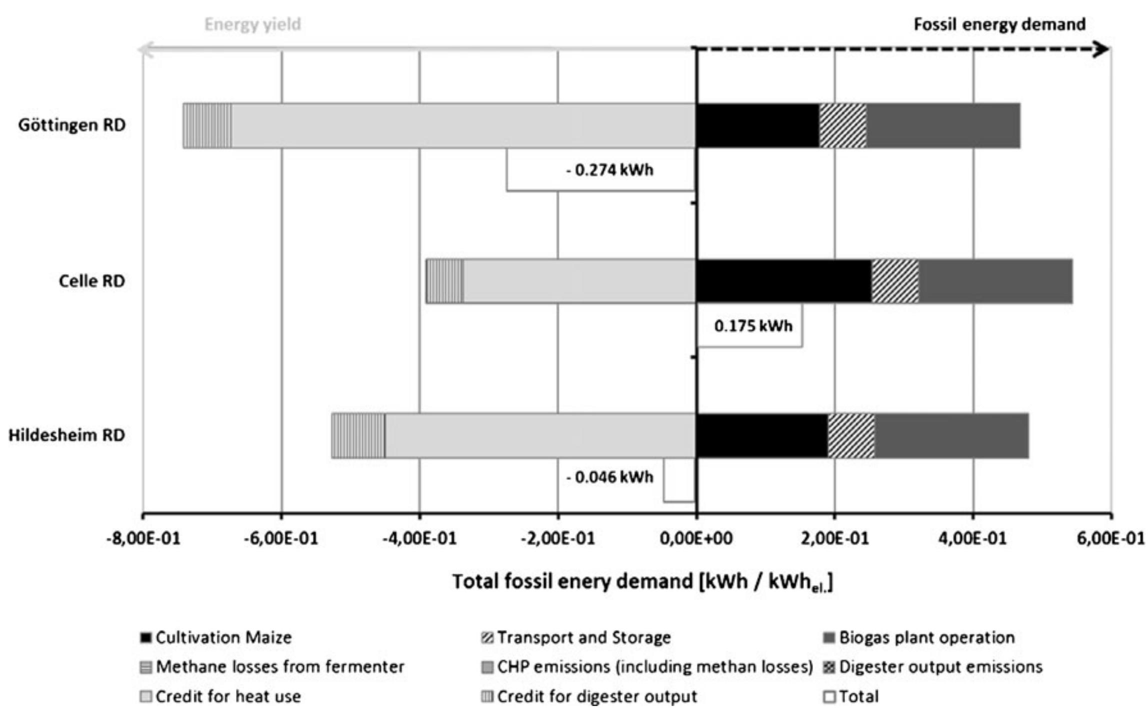

Fig. 2 Accumulated fossil energy demand of power generation from biogas in Göttingen, Celle, and Hildesheim [*left side* energy yield, *right side* energy demand, and *lower bar* total result]

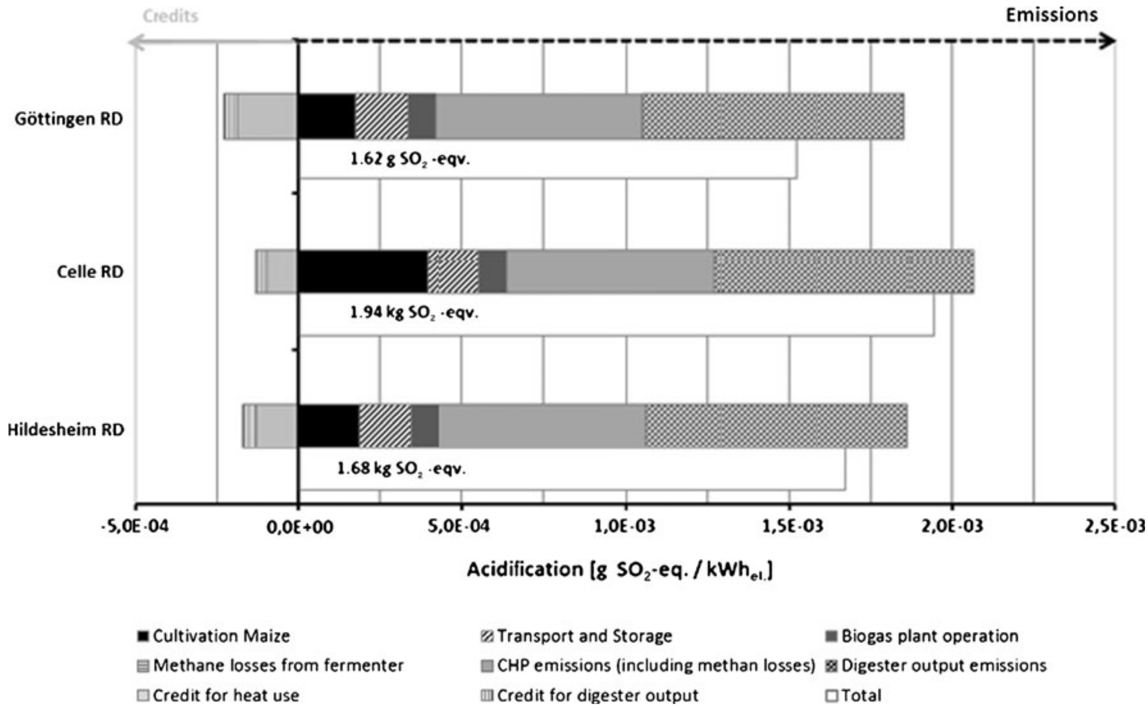

Fig. 3 Acidifying emissions of power generation from biogas in Göttingen, Celle, and Hildesheim [*left side* credits of acidifying emissions, *right side* acidifying emissions, and *lower bar* total result]

By system expansion, the use of waste heat from CHP as a by-product of the power generation of biogas is included in the system boundaries. The environmental burden of generating the same amount of heat from oil and gasoline were credited to this system. Another allocation procedure, which is recommended by the ISO standard (ISO 14044 2006), is to allocate the physical properties (e.g., mass, calorific value, and exergy). The exergy allocation in the LCA of power generation from biogas

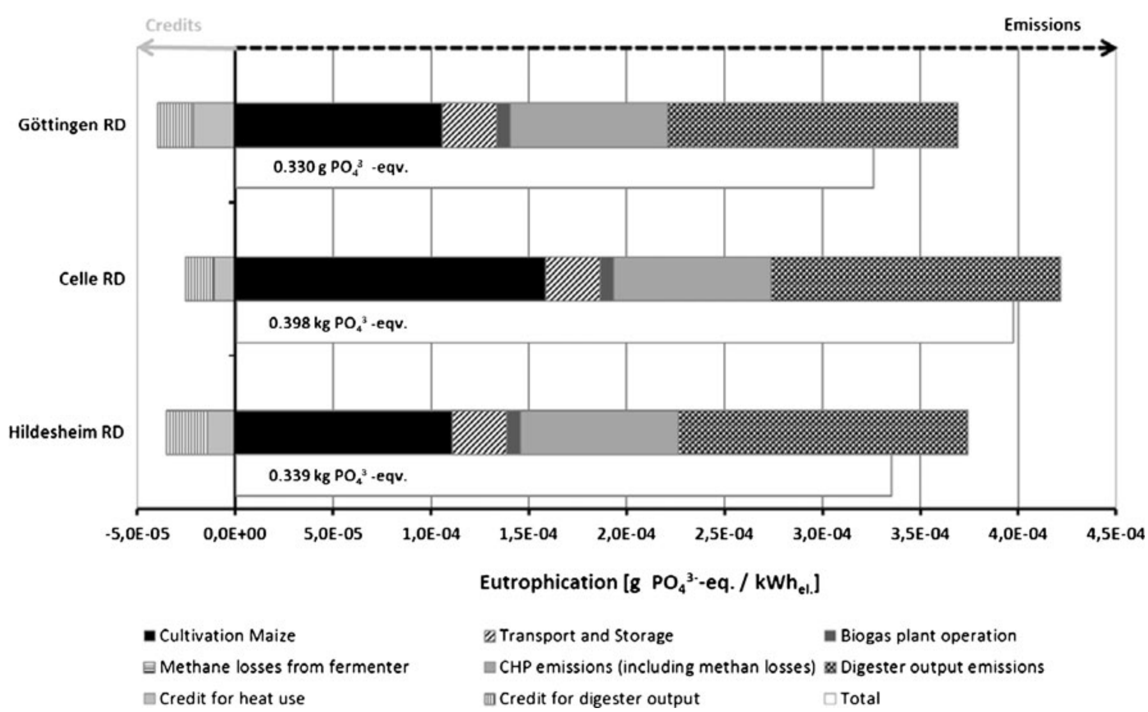

Fig. 4 Eutrophication emissions of power generation from biogas in Göttingen, Celle, and Hildesheim [*left side* credits of eutrophication emissions, *right side* acidifying emissions, and *lower bar* total result]

does not consider the total amount of heat production but only the share of the used heat. Figure 5 shows the differences in the final results of the production and use of biogas for power generation between system expansion and exergy allocation.

This sensitivity analysis clarifies the influence of the allocation procedure for estimating the environmental burdens of power generation from biogas. The impact categories of the GHG emissions and the total fossil energy demand show higher results in exergy allocation instead of system expansion and credits for heat use. The results of acidification and eutrophication show an opposite trend: in the case of exergy allocation, the emissions are lower than in the case of system expansion. This outcome results from the avoided heat generation from fossil oil and gasoline, which was credited to the system, and has a greater impact on the GHG emissions and total fossil energy demand than on acidification and eutrophication. Exergy allocations affect all of the considered impact categories to the same degree. Thus, the exergy allocations reduce the regional difference in the results of the GHG emissions and total fossil energy demand but increase the difference in acidification and eutrophication. Consequently, the allocation procedure influences the regional differences in the environmental burdens of power generation from biogas but does not eliminate them. The regional differences remain present.

4 Discussion

Our results refer to the cultivation of energy maize and the production and use of biogas from energy maize. The GHG emissions associated with the cultivation of energy maize range from 45.4 to 57.7 kg CO_2 eq./t of fresh maize. The results from IFEU (2008a), concerning basic data for the GHG balances of biogas process chains of 55.254 kg CO_2 eq./t of fresh maize, fall within the range of this calculation. However, there are some differences in the calculations. For example, nitrogen uptake was completely calculated as mineral fertilizer use by IFEU (2008a), whereas the use of 20 m^3/ha of digester output substitutes a part of the mineral fertilizers in our study (e.g., approximately 72.8 kg/ha of nitrogen fertilizers). Therefore, the GHG emissions of this study might be higher without the use of digester output as a fertilizer substitute. These results range from 58.59 kg CO_2 eq./t of fresh maize in Goettingen to 72.321 kg CO_2 eq./t of fresh maize in Celle. In addition, the IFEU (2008a) did not consider any regional parameters in their balance, such as yield level, specific nitrogen demand, and fieldwork depending on the soil type. These variables could influence the results of the GHG emissions and could explain the differences in the results for the GHG emissions.

Another point that could influence the results of the GHG emissions for the cultivation of energy maize are direct and indirect land use changes. However, in these calculations, the influence of direct and indirect land use change is not taken into account due to the lack of district-level data. Studies by Luo et al. (2009) and Kim and Dale (2009) indicate that this influence could enhance the effect of regional variation. Indirect land use change is often discussed with biofuels. Moreover, in Germany, energy crops are cultivated on set-aside land. However, if the development of bioenergy continues, indirect land use change will also become increasingly important for biogas production. Direct land use change, especially the plowing of grassland in Germany, is linked to the cultivation of energy maize and biogas production. Nevertheless, no reliable base currently exists to obtain a realistic estimate of which part of the plowed grassland in Germany is used for cultivating energy crops. Nevertheless, direct land use change can be assumed to have a higher impact in Celle than in Goettingen or Hildesheim. That's why the cultivation of energy crops is more important in Celle than in the two other districts (see Section 2.2).

Additionally, direct and indirect nitrous oxide emissions from the soil were calculated following the method of the IPCC (2006) without consideration of the soil types, climatic conditions, and methods of applying nitrogen fertilizers. This aspect is under continuous investigation, including field trials, and could further influence the results of our study.

The GHG emissions associated with the production and use of biogas from maize range from 0.179 to 0.058 kg CO_2 eq./kWh_{el}. The results from the IFEU (2008a) of 0.207 kg CO2 eq./kWh_{el} demonstrate higher emissions than the results in our study. This difference depends primarily on the lower share of used heat. The IFEU (2008a) calculated a 20 % share of used heat, which is lower than our values. The values collected in this study range from 30 to 60 % heat use. The share of used heat (60 % on average) in the district of Goettingen seems especially high. However, Goettingen has fewer installed biogas plants than the two other districts with mostly efficient heat use concepts, e.g., bioenergy villages or thermal process energy production. The example of Goettingen is not yet typical, but it does highlight the fact that regional parameters are important for the LCA of biogas.

The results of eutrophication and acidification were mainly affected by the emissions from the CHP and the emissions from the application of digester output. These aspects were equally calculated for each district without regional parameters and local factors. However, a study by Scheller (2006) shows that the amount of nutrient losses, such as phosphate and nitrate, depends on the regional soil type. The loss and leaching of nitrate from clay soil is lower than from sandy soil, which is associated with a higher permanence of soil water in the clay than in sand (Scheller

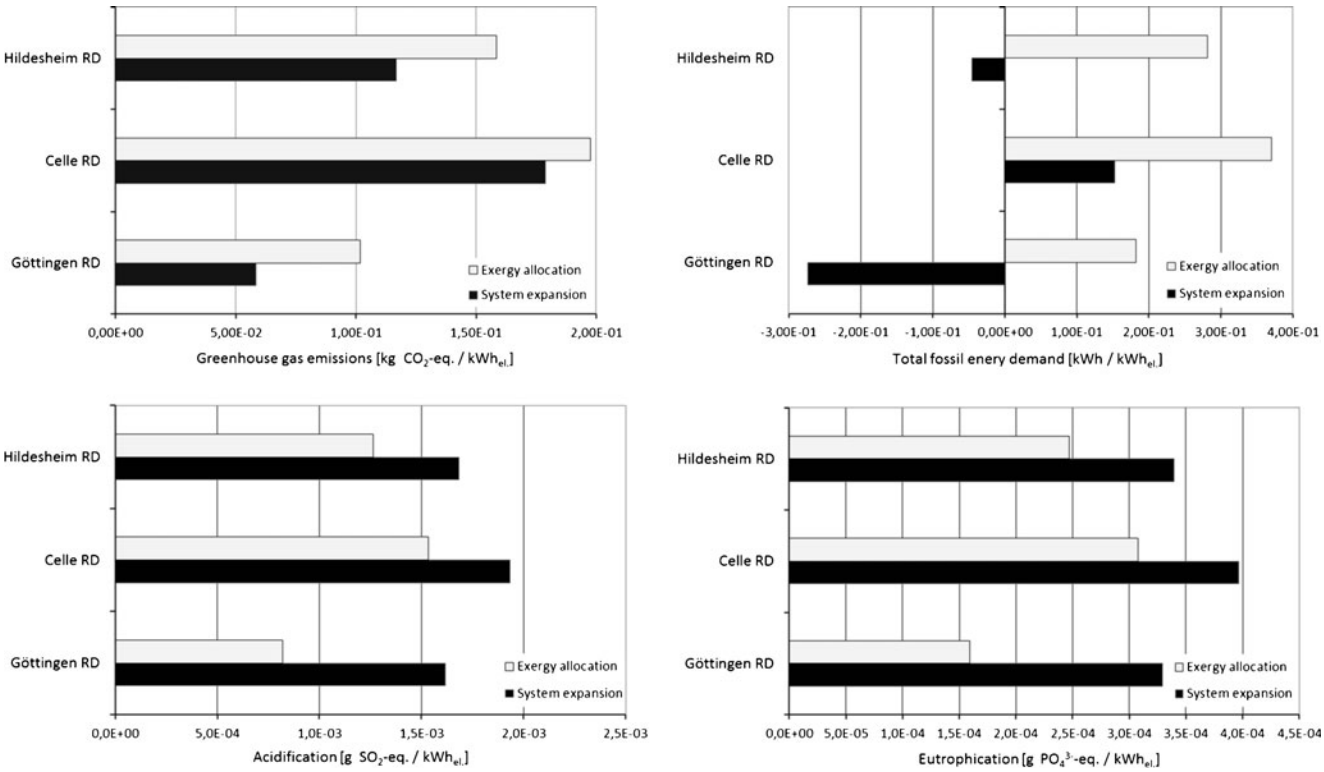

Fig. 5 Sensitivity analyses: effects of allocation processes for heat use on the impact assessment of power generation from biogas [*white bar* exergy allocation, *black bar* system expansion allocation]

2006). Applying the digester output increases this effect. Consequently, a regional consideration of digester output application could enhance the effect of variations in the results of the LCA. Further studies should investigate this aspect in combination with a nutrient surplus in regions with intensive livestock farming.

Other influencing parameters, which were not investigated in this study, are the distinctions in engineering processes. The findings of the IFEU (2008b) show the influence of open versus closed fermenters because the direct emissions from the fermenters can contribute to 25–75 % of the overall GHG emissions.

5 Conclusions

To summarize, the findings of this study suggest that regional variations occur in all of the impact categories investigated. This conclusion has been determined by the LCAs of biogas production from maize and the conversion of biogas into electricity. The cultivation of maize and using heat from the CHP are the most important influencing parameters for the impact categories of GHG emissions and total fossil energy demand. A sensitivity analysis of the allocation procedures for heat use shows that exergy allocations reduce the regional difference in the results of the GHG emissions and total fossil energy demand compared to system expansion.

The distinctions in maize cultivation that cause differences in the LCA results are the different amounts of fertilizers, irrigation demand, and fieldwork. Regional variations in acidification and eutrophication are mainly caused by the irrigation (specifically for pump operation) of the maize crop; however, emissions from the digester output and emissions from the CHP account for the largest share of acidification and eutrophication.

Even without including the additional aspects that are pointed out in the discussion, our results show the impact of the regional parameters on LCAs and support the studies of Chiaramonti and Recchia (2010) and Kim and Dale (2009). Therefore, the LCA of biogas technologies should consider regional parameters. This procedure is necessary, especially if the LCA studies are used for generalized evaluations, such as statements concerning the possible climate protection potential of biogas. Only if regional variations are considered will the results of the GHG emissions, for example, be representative, as the results could vary from one region to another. In the case of direct and indirect land use change, the results could even lead to higher emissions than would arise from the use of fossil fuels. In short, the LCAs of bioenergies should always account for regional parameters.

References

ASUE (2011) BHKW Kenndaten 2011: Module, Anbieter, Kosten. Arbeitsgemeinschaft für sparsamen und umweltfreundlichen Energieverbrauch e.V. (Ed), Berlin, Germany

Bachmaier J, Gronauer A (2008) Klimabilanz von Biogasstrom. Bavarian Agricultural Research Institute (LfL), Freising-Weihenstephan

Chiaramonti D, Recchia L (2010) Is life cycle assessment (LCA) a suitable method for quantitative CO_2 saving estimations? The impact of field input on the LCA results for a pure vegetable oil chain. Biomass Bioenerg 34:787–797

Commission of the European Communities (2005) Biomass action plan, Brussels. Available at http://europa.eu/legislation_summaries/energy/renewable_energy/l27014_en.htm. Accessed 26 Jan 2011

DMK (2011) Deutsches Maiskomitee (German Maize Committee). Available at http://www.maiskomitee.de/web/public/Fakten.aspx/Statistik/Europ%C3%A4ische_Union/Anbaufl%C3%A4che_Silomais. Accessed 02 Sept 2011

EEG (2009) Gesetz für den Vorrang Erneuerbarer Energien (Reneable Energy Act)

FAO (2009) Food and Agriculture Organization of the United Nations. Available at http://faostat.fao.org/site/567/default.aspx#ancor. Accessed 02 Sept 2011

FNR (2011) Fachagentur Nachwachsende Rohstoffe (Agency of Renewable Resources), Cultivation of renewable resources in Germany. Available at http://www.nachwachsenderohstoffe.de/service/daten-und-fakten/anbau/ Accessed 02 Sept 2011

Fricke E, Riedel A (2010) Felberegnung optimieren: Wasserverbrauch reduzieren. Available at http://www.fachverband-feldberegnung.de/pdf/Feldberegnung_optimieren_220410.pdf. Accessed 03 Feb 2011

Hartmann K (2006) Life cycle assessment of industrial scale biogas plants. Dissertation, University of Göttingen

GEMIS (2010) Global emission model for integrated systems. Ökoinstitut Germany. Available at http://www.oeko.de/service/gemis/de/index.htm. Accessed 18 Dec 2010

Guinée JB et al. (2002) Handbook on life cycle assessment—an operational guide to the ISO Standards. ISBN 1-4020-0228-9, Kluwer, Dordretch

IFEU (2008a) Basisdaten zu THG-Bilanzen für Biogas-Prozessketten und Erstellung neuer THG-Bilanzen. Available at http://www.ifeu.de/oekobilanzen/pdf/THG_Bilanzen_Bio_Erdgas.pdf. Accessed 13 Feb 2011

IFEU (2008b) Optimierungen für einen nachhaltigen Ausbau der Biogaserzeugung und -nutzung in Deutschland. Available at http://www.ifeu.de/landwirtschaft/pdf/BMU-Biogasprojekt%202008-Zusammenfassung.pdf. Accessed 13 Feb 2011

IPCC (Intergovernmental Panel on Climate Change) (2006) N_2O Emissions from managed soils, and CO_2 emissions from lime and urea application. Available at http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf. Accessed 03 Feb 2011

IPCC (2007) WGI Fourth Assessment Report. Available at http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml. Accessed 03 Feb 2011

ISO 14040 (2006) Environmental management—life cycle assessment—principles and framework

ISO 14044 (2006) Environmental management—life cycle assessment—requirements and guidelines

Juri C, Benetto E, Koster D, Schmitt B, Welfring J (2009) Life cycle assessment of biogas production by monofermentation of energy crops and injection into the national grids. Biomass and bioenergy 34:55–66

Kim S, Dale BE (2009) Regional variations in greenhouse gas emissions of biobased products in the United States—corn based ethanol and soybean oil. Int J Life Cycle Assess 14:540–546

KTBL (2006) Energiepflanzen. Association for Technology and Structures in Agriculture, Darmstadt, Germany

KTBL (2009) Faustzahlen Biogas. Association for Technology and Structures in Agriculture, Darmstadt, Gemany

LBEG (2010) Bodenschätzungsdaten für die Metropolregion, Niedersächsisches Bodeninformationssystem NIBIS®. Lower Saxony State Office for Mining, Energy and Geology, Hannover, Germany

Lewandowski I, Böhmel C (2009) Angebaute Biomasse—Zucker und Stärkepflanzen. In: Kaltschmitt M (ed) Energie aus Biomasse: Grundlagen. Techniken und Verfahren, Springer, Berlin, pp 76–134

Liebetrau J, Daniel-Gromke J, Reuschel C, Oehmichen K, Clemens J, Hafermann C, Weiland P, Fiehe J (2011) Bewertung klimarelevanter Gase aus landwirtschaftlichen Biogasanlage auf Basis von Emissionsmessungen. In: KTBL (ed) Biogas in der Landwirtschaft. Association for Technology and Structures in Agriculture, Darmstadt, Germany, pp 185–195

Luo L, van der Voet E, Huppes G, de Haes HAU (2009) Allocated issues in LCA methodology: a case study of corn stover-based fuel ethanol. Int J Life Cycle Assess 14:529–539

LSKN (2007) Bodennutzung und Ernte 2007, Statistische Berichte Niedersachsen. Centre for Statistics and Communication Technologies of Lower Saxony, Hannover Germany. Available at http://www.nls.niedersachsen.de/Tabellen/Landwirtschaft/ernte_2003/texte/Ernte07.pdf. Accessed 11 Feb 2011

LWK (2010a) Chamber of Agriculture Lower Saxony. Available at http://www.lwk-niedersachsen.de/index.cfm/portal/pflanze/nav/341/article/14022.html. Accessed 11 Feb 2011

LWK (2010b) Chamber of Agriculture Lower Saxony. Available at http://www.lwk-niedersachsen.de/index.cfm/portal/2/nav/340/article/5924.html. Accessed 11 Feb 2011

LWK (2010c) Düngeempfehlung der Landwirtschaftskammer Niedersachsen, Richtwert-Deckungsbeiträge 2009. Chamber of Agriculture Lower Saxony, Oldenburg, Germany

Majer S, Schröder G (2009) Erläuterungspapier zum Entwurf der Biomasse Nachhaltigkeitsverordnung vom 05.12.2007. Available at http://www.ufop.de/downloads/RZ_Erlaeuterung_BioNachV_170108.pdf. Accessed 15 Feb 2011

PE International (2010) GaBi 4.4 software system and database for life cycle balances. Leinfelden-Echterdingen, Germany

Scheller (2006) Diffuse pollution of waters from agricultural land use, 18. Wissenschaftliche Fachtagung Landwirtschaft und Grundwasser—Stoffeinträge analysieren, bewerten und vermeiden—Band 139, Landwirtschaftliche Fakultät der Rheinischen Friedrich-Wilhelms-Universität Bonn, Germany

TLL (2007) Leitlinie zur effizienten und umweltverträglichen Erzeugung von Silomais zur Fütterung und Nutzung als Gärsubstrat in Biogasanlagen. Thuringian State Institute for Agriculture, Jena, Germany

VDI 4600 (1997) VDI guidelines—cumulative energy demand—terms, definitions, methods of calculation

Institute W (2005) Analyse und Bewertung der Nutzungsmöglichkeiten von Biomasse. Wuppertal Institute for Climate, Environment and Energy